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Optimizing optical precision of an image using curved focal plane technology

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ABSTRACT

The quality of an image captured by the human eye is typically better than that obtained relative to artificial images created by cameras or telescopes. This is because humans have curved retinas. In contrast, conventional imaging cameras have flat sensors that are not well matched to the curved focal surfaces of a camera lens or telescope objective. Thus, the image cannot be at the same focus across the entire sensor field of view. It is hypothesized that as the surface of the sensor approaches the curvature of the camera lens or telescope, the image quality increases. To test this, a commercially available ray tracing software was used. The curvatures were varied from flat (0 mm) to 12 mm. As the curvature reached 9 mm, the Petzval curvature, the quality of the captured images from the camera significantly improved. However, as the curvature increased beyond 9 mm, the quality of the artificial image decreased. In addition, a simulation of a classical Cassegrain telescope was also made. For the telescope, the curvatures were varied from 0 mm to 500 mm. As the curvature approached the telescope's focal surface curvature of 350 mm, the distortion decreased. In addition to the optical simulations, two images were generated: one with a camera and the other by a reconstruction process. The latter was reconstructed by using the central part of images taken along that curve to create an image. A comparison of these images demonstrates the superior image produced with the latter method. Devices such as cameras and telescopes with curved focal plane array detectors produce images with higher quality than those produced using devices equipped with flat focal plane array detectors.

Keywords: Petzval curvature, Cameras, Telescopes, Curved Focal Plane, Aberrations

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1. INTRODUCTION

Cameras are finding their utility in many commonly used devices including smart phones, computers, cars etc. Modern day lifestyle increasingly depends on images, both still and video, captured by cameras. Obtaining images with the highest quality that are free of distortions is thus becoming a necessity and optimizing the optical accuracy of an image is essential, especially as the detectors get larger in telescopes and satellites.

Optical imaging systems in small and large scale devices have a curved focal surface. However, charged coupled device (CCD) or complementary metal–oxide–semiconductor (CMOS) sensors in modern cameras, which are based on silicon chip technology, have flat focal plane array detectors. To avoid the blurring of the image, additional lenses and/or mirrors are used to map or "flatten" the curved focal surface onto these sensors. However, field flatteners alter the imaging system focal length and decrease the field of view (FOV) and sensitivity of the imaging system, add to the system's bulk and weight, and also cause additional distortions in the final image. Zooming features that are available on many cameras require lenses and mirrors to undergo numerous movements,

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which can affect their reliability, particularly those in much larger devices like those in ground- and satellite-based telescopes.

In contrast to manufactured imaging systems, the human eye's detector, the retina, is a curved surface. Through our research of focal plane array detector optics, we hypothesized that the curvature of the detector allows the image sensor to be placed nearer or farther from the focal plane of the system which can vary the image quality of the optical system. We found that an undamaged human eye produces the highest quality optical image without the need for any lenses and mirrors. The eyes of other animals also have curved retinas. Our results support our initial hypothesis that an optimized curvature enables better optical precision capabilities in optical systems.

It is interesting to understand how the quality of image produced by cameras or telescopes would be affected if conventionally used flat focal plane array detectors were replaced by curved ones. It is believed that if a curved focal plane array detector with a curvature that matches the Petzval curvature of the optical system can be used, this optical system will produce the best quality optical image with minimal aberrations.[1,2] An optimized curvature can also eliminate the need for additional field flattening lenses and mirrors, thereby making the system lighter and smaller. This system would have minimal or no moving parts, reducing the potential for system failures due to damage or wear-and-tear traditionally associated with moving parts.

In order to understand the effects of the focal plane array detector's curvature on image quality, a series of optical simulations were performed. Virtual optical systems were constructed with varying degrees of curvature, ranging from 0 mm for a flat focal plane array detector to 12 mm for a curved focal plane array detector in a camera system and 0 mm for a flat focal plane array detector to 500 mm for a curved focal plane array detector in a telescope system. The independent variable is the curvature of the focal plane. The dependent variable is the quality of the optical image as measured by the amount of chromatic aberration, spherical aberration, coma and astigmatism. Each measurand is described in more detail below. It is hypothesized that as the curvature of the focal plane approaches the curvature of the human eye, the optical quality of an image will increase and the number of lenses and mirrors necessary to achieve a greater FOV and image resolution will be reduced.

The goal was to analyze two optical systems – a ground-based space telescope and a consumer hand-held camera. Using optical modeling software for ray tracing, which is described in more detail below, calculations for 5 major aberrations (chromatic, spherical, coma, astigmatism, and distortion (barrel or pincushion)), were performed, factoring in the FOV and image resolution for both the telescope and camera.[3] Two different configurations were used: (1) a conventional flat focal plane array detector with field-flattening optical components and (2) a curved focal plane array detector with varying degrees of curvature approaching that of the human eye with an optical system that makes use of fewer lenses. The curved set up was designed to have fewer optical surfaces to remove aberrations and optimize the quality of the images. Possible manufacturing techniques that can be employed to achieve such curved focal plane array detectors in a cost-effective manner were explored.

2. BACKGROUND

2.1 Measurands to determine the quality of optical images.

Aberrations limit the performance of optical lenses and the devices making use of the lenses to generate images. These aberrations are important to understand to assess the performance of lenses in optical systems. The key types are described below.[4]

2.1.1 Chromatic Aberrations

Chromatic aberrations are optical aberrations that occur when a lens is unable to focus all colors on the focal plane. This is due to dispersion, which is the variation in the refractive index of the lens elements based on changes in the wavelength of light. It appears as fringes of color on the edges of objects.

2.1.2 Spherical Aberrations

Spherical aberrations are optical aberrations that exist due to spherical elements, such as lenses and mirrors. When light rays strike these surfaces off-center, they are refracted or reflected, respectively, more or less than light rays that strike closer to the center. It appears as "fuzziness" around the edge of objects.

2.1.3 Coma

Coma, or comatic aberrations, are optical aberrations caused by either off-axis illumination or defects in a lens or specific optical setups that makes point objects appear as if they have a tail, like a comet. This is a result of variations in magnification.

2.1.4 Astigmatism

Astigmatism is an optical aberration caused by variations in the focal length, resulting in a defocused or "blurry" image. The focal length variations cause parallel rays in different planes to intercept different foci, preventing a focused or "clear" image from forming.

2.1.5 Distortion

Distortion is an optical aberration, usually associated with zoom lenses. Distortion is a deviation from the rectilinear projection, i.e., straight lines in an image do not remain straight, but rather appear bowed in or out. This is due to variance in magnification across the image. However, since there is no loss of information, an image can be corrected algorithmically for distortion. Two types of distortion exist: barrel distortion and pincushion distortion. With barrel distortion, the image magnification decreases as the distance from the optical axis increases while in pincushion distortion, the image magnification increases as the distance from the optical axis increases.

2.2 Ray Tracing

Ray tracing is an optical simulation method that consists of determining many light ray paths from a light source or image. The data collected can be used to understand the effectiveness of an optical system, aberrations, and other critical information. For this research, an optical modeling/ray tracing software called OSLO^{TM} was used.

2.3 Optical design of a ground-based space telescope

The optical design of the telescope used in this research was the classical Cassegrain telescope. This telescope design is popular in astronomical telescopy. The arrangement of mirrors is designed to focus incoming light at a point close to the main light-gathering mirror. The light is reflected to a secondary mirror, which then reflects the light back through a small hole in the main mirror to the eyepiece. This "folded up" layout allows the tube design to be short and compact, making it easy to transport and use in the field. This design is discussed further in Section 3.1.

2.4 Optical design of a consumer hand-held camera

The optical design of the camera used in this research was a standard triplet lens array. This design minimizes the effects of aberrations seen in more complicated lens systems involving field flattening lens systems and is discussed further in Section 3.1.

3. MATERIALS AND METHODS

3.1 Optical System

Curved focal plane array detector optics were modeled in two virtual optical systems using optical ray tracing simulation software, called OSLO^{TM}. The software package was deployed on a desktop computer with an Advanced Micro Devices (AMD) Ryzen processor and Windows 10 operating system, which satisfied the required computing needs to run the software. The software package was used to perform all ray tracing analyses and calculate the associated aberrations.

Two optical systems were simulated. The first was a ground-based telescope optical system and the second was a consumer hand-held camera optical system. Both systems were created virtually using the principals described above in Section 2.3 and 2.4, respectively. Briefly, each system was simulated with a flat focal plane array detector configuration as a control (i.e., no curvature) and as an optically curved system with multiple lenses. Simulations for each system produced data representative of no optical curvature for use as the control data and data that were representative of a system with optical curvature for use as sample data to compare with the control data.

The optical design of a commonly used telescope makes use of a corrected Cassegrain architecture as shown in Figure 1. This telescope design consists of a flat focal plane array detector and triplet field flattening optics. The triplet field flattening optics are typically used to flatten the native field curvature. This causes the captured image within the telescope to converge only on the flat surface with various types of aberration. This type of configuration limits the performance of the telescope because there are numerous optical surfaces which decrease the telescope's FOV, sensitivity, aperture size, and other aberrations such as those described above in Section 2.1.

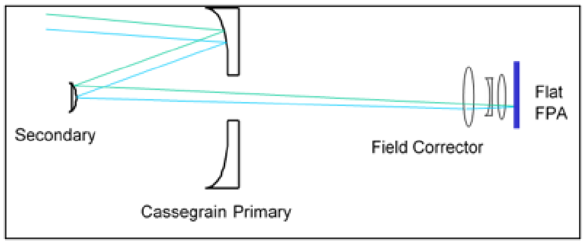


Figure 1: Optical design of a common ground-based space telescope. Light is focused through a series of secondary and primary lenses to a field corrector and a flat focal plane array detector.

The optical design of a commonly used consumer hand-held camera is shown in Figure 2. This design uses a flat focal plane array detector in conjunction with several field flattening lenses similarly to the common ground-based space telescope. Images captured by a camera with this type of optical system will also have numerous optical aberrations and limited FOV, sensitivity and significantly reduced image clarity.

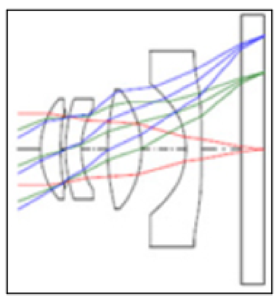


Figure 2: Optical design of a consumer hand-held camera lens system showing colors of light entering into the system on the left. Once in the system, light is focused through a series of lenses to a flat focal plane array detector (shown on the right).

The average radius of curvature of a human eye is approximately 9 mm.[5] Since tradiational hand-held phone cameras use a similar design, the Petzval surface for these cameras also has a radius of curvature of approximately 9 mm. Based on this, the curvature of the focal plane array detector in the consumer hand-held camera simulation was varied from 0 mm (flat) to 12 mm to capture the curvature dimension of the human eye (i.e., as if a human eye was looking through the camera lenses). The curvature was varied at 3 mm intervals (see Table 1).

The curvature used for a ground-based space telescope was approximately 350 mm, based on the calculated Petzval curvature of a Cassegrain Telescope. Based on this, the curvature of the focal plane array detector in the ground-based space telescope simulation was varied from 0 mm (flat) to 500 mm to capture the typical curvature dimension of a general telescope. The curvature was varied at 50 mm intervals beginning with 300 mm (see Table 2). For each radius of curvature in each simulation, spherical aberration, chromatic aberration, coma and astigmatism was calculated from the ray tracing data obtained using OSLO$^{\mathrm{TM}}$ software.

3.2 Ray Tracing Analysis

For both optical systems discussed above, detailed ray tracing analyses was performed using the OSLO™ software package to calculate the aberrations described in Section 2.1. Keeping the number of optical elements constant, the curvature of the focal plane detector array was varied, as described in Section 3.1 and the aberrations were calculated.

3.3 Optical modeling validity tests

Experiments were performed to demonstrate the validity of the ray tracing data obtained from the optical simulations. A simplified ray trace diagram for an imaging system with a flat focal plane array detector is shown in Figure 3. As can be seen below, the rays near the optical axis converge on the flat focal plane array detector, but the rays away from the optical axis tend to converge radially outward from the central axis away from the flat focal plane array detector.[6,7] In fact, they converge along a curved region called the Petzval curvature of this optical system. If a curved focal plane array detector with the curvature matching the Petzval curvature was used instead of the flat focal plane array detector, then all the rays can converge on the focal plane resulting in an image that is free of aberration and will have greater image clarity. Since the availability of a curved focal plane array detector was extremely rare (or non-existent), a camera with a flat focal plane array detector was used.

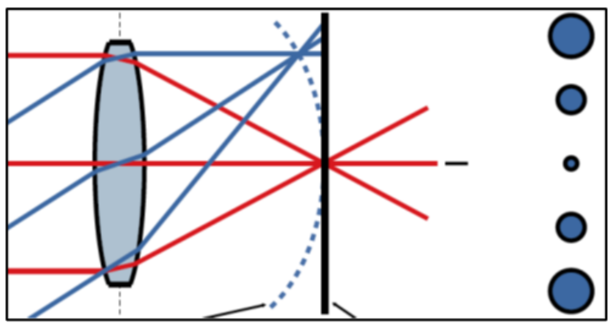


Figure 3: Simplified ray diagram of an imaging system, demonstrating the effect of deviation from the Petzval curvature. The dashed line represents the Petzval surface and the dots on the right of varying sizes represents the defocusing of the incident light rays.[7]

A consumer hand-held camera was used to capture the image of a given scene (a tree) as a reference image. A small aperture was then placed at the center of the camera to allow the pixels of the image to be near the center of the focal place, i.e., close to the optical axis, to capture the image. This camera and aperture arrangement was moved along the focal plane to capture of the scene (Figure 4). The total image was then reconstructed from the individually captured images. The quality of the reconstructed image was compared to the image captured without the aperture.

4. RESULTS AND DISCUSSION

4.1 Consumer hand-held camera results

Ray trace analysis plots obtained for the consumer hand-held camera are shown in Figure 5 and Figure 6 using a flat focal plane array detector and a curved focal plane array detector, respectively. From the data in these figures, the spherical aberration, chromatic aberration, astigmatism and coma were calculated (see Table 1). Variation of the aberrations as a function of curvature of the focal plane array detector is shown in Figure 7.

As shown in Figure 7, as the curvature increased, the aberrations decreased. When curvature of the focal plane array detector approached the Petzval curvature, the aberrations approached a minimum value. In contrast, as the curvature of the focal plane array detector exceeded the Petzval curvature, the aberrations increased. Since the quality of image is directly related to the aberrations, the quality of an image is expected to improve as the curvature is increased until it reaches the curvature of human eye, and it will degrade as the curvature is

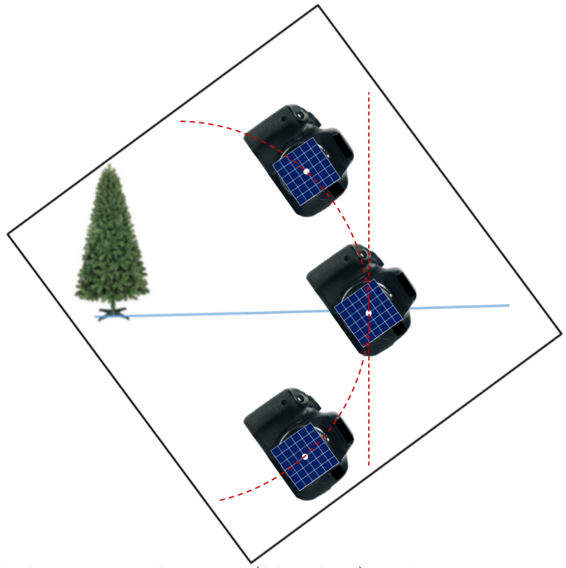


Figure 4: Camera with flat focal plane array detector (blue line) and an aperture moved along the Petzval surface (red dashed line) demonstrating that the flat focal plane array detector only captures a point on the image of the tree and the curved focal plane array detector captures the entire image of the tree. See images in Fig. 12a, 12b, and 12c.

increased further.[8] Among all the aberrations calculated, the one that changed the most was astigmatism and the one that changed the least was chromatic aberration.

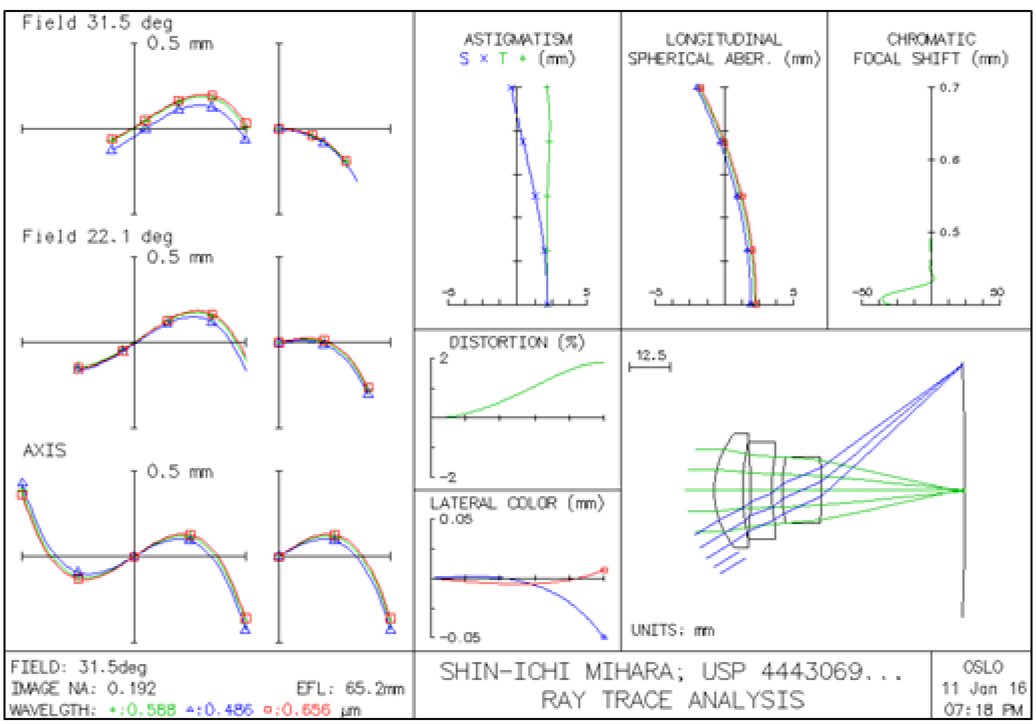


Figure 5: Ray trace analysis plot for a camera with a flat focal plane array detector.

Table 1
Aberrations as a function of focal plane array detector curvature for a camera

Curvature (mm)	Astigmatism (mm)	Coma (Distortion) %	Chromatic Aberration (x 10 mm)	Spherical Aberration (mm)
0	2.4	2	3.6	4.6
3	1.2	1.6	1.6	2.5
6	0.6	1.1	1	1.3
9	0.1	0.5	0	0.33
12	1.6	0.9	1.8	1.9

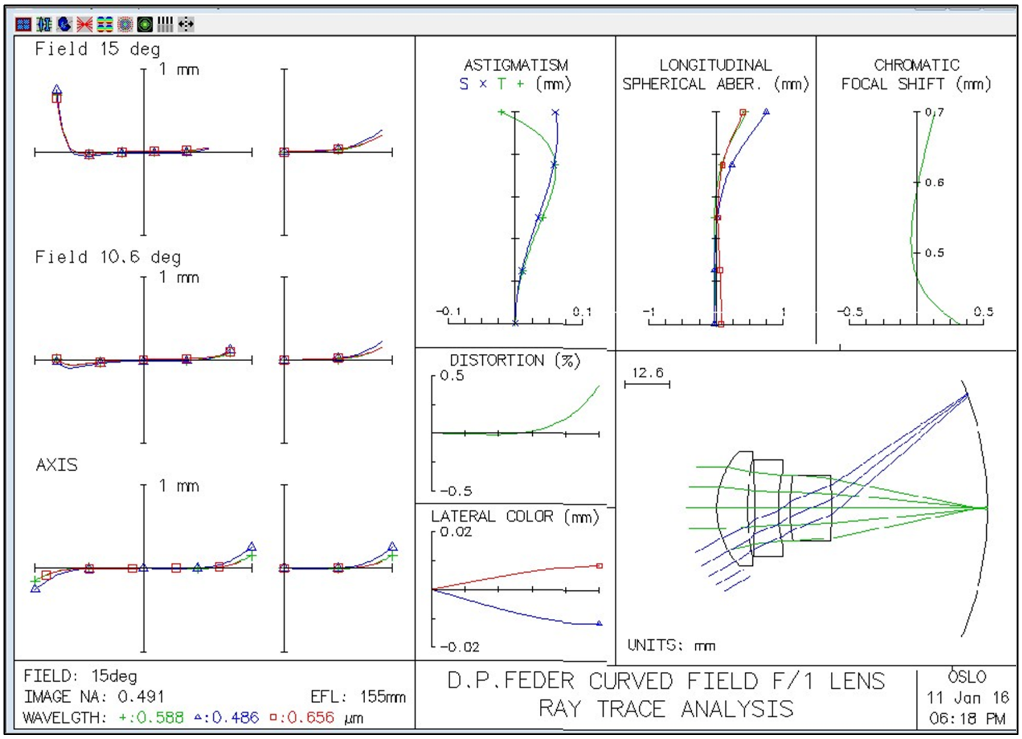


Figure 6: Ray trace analysis plot for a camera with a focal plane array detector with a curvature of 9 mm.

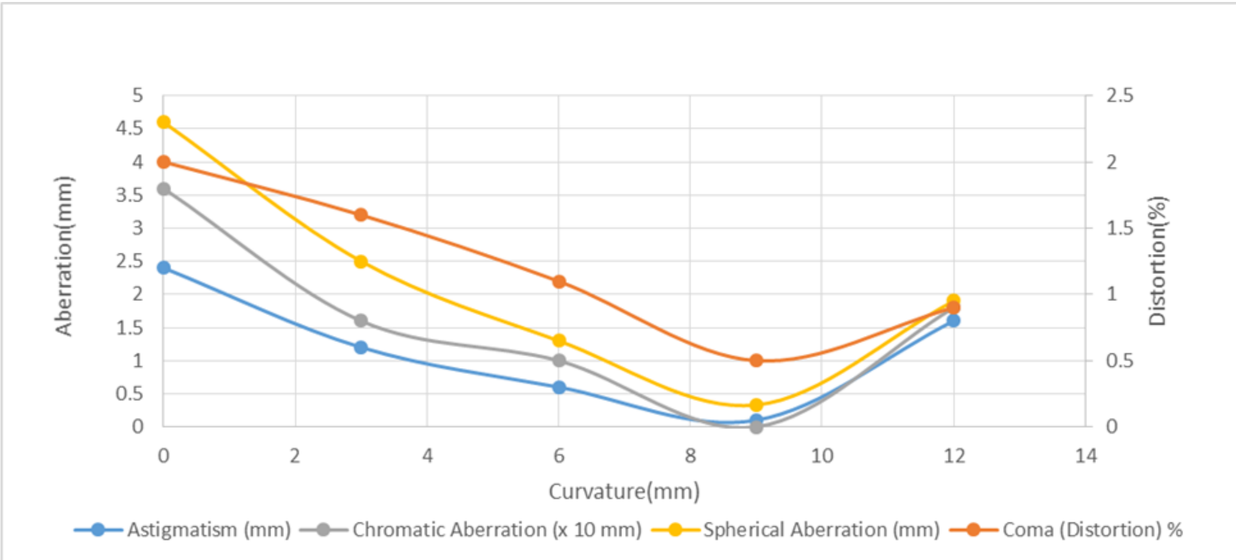


Figure 7: Variation of aberrations as a function of curvature of the focal plane array detector for a camera system.

4.2 Ground-based space telescope results

Ray trace analyses plots obtained for a Cassegrain telescope with a flat focal plane array detector and a curved focal plane array detector are shown in Figures 8 and 9, respectively. From the data in these figures, the spherical aberration, chromatic aberration, astigmatism and distortion (coma) were calculated (see Table 2). Variation of the aberrations as a function of curvature of the focal plane array detector is shown in Figure 10. As shown in Figure 10, it was observed that the calculated aberrations decreased as the curvature increased from 0 mm to 350 mm. As the curvature of the focal plane array detector approached the typical curvature in a ground-based space telescope system (approximately 350 mm), the aberrations approached a minimum value, suggesting the quality of an image will increase as the curvature increases to 350 mm. As the optical curvature of the focal plane array detector increases beyond 350 mm, the magnitude of the aberrations increase, suggesting the quality of an image will decrease beyond this point.

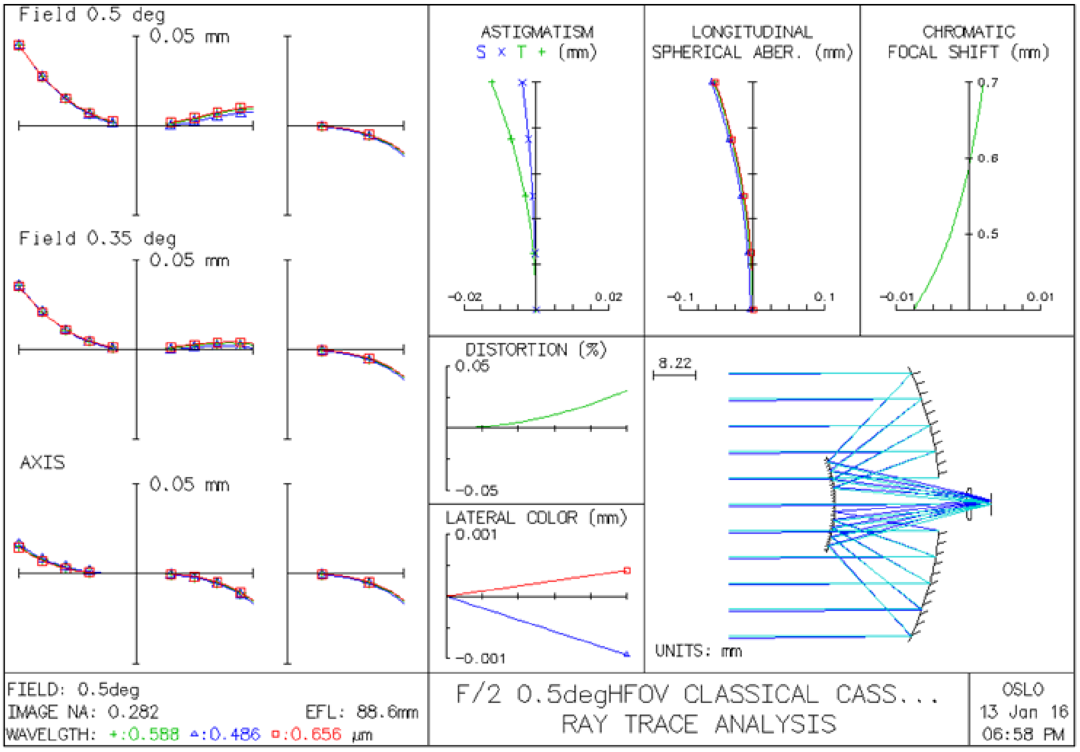


Figure 8: Ray trace analysis plot for a telescope with a flat focal plane array detector.

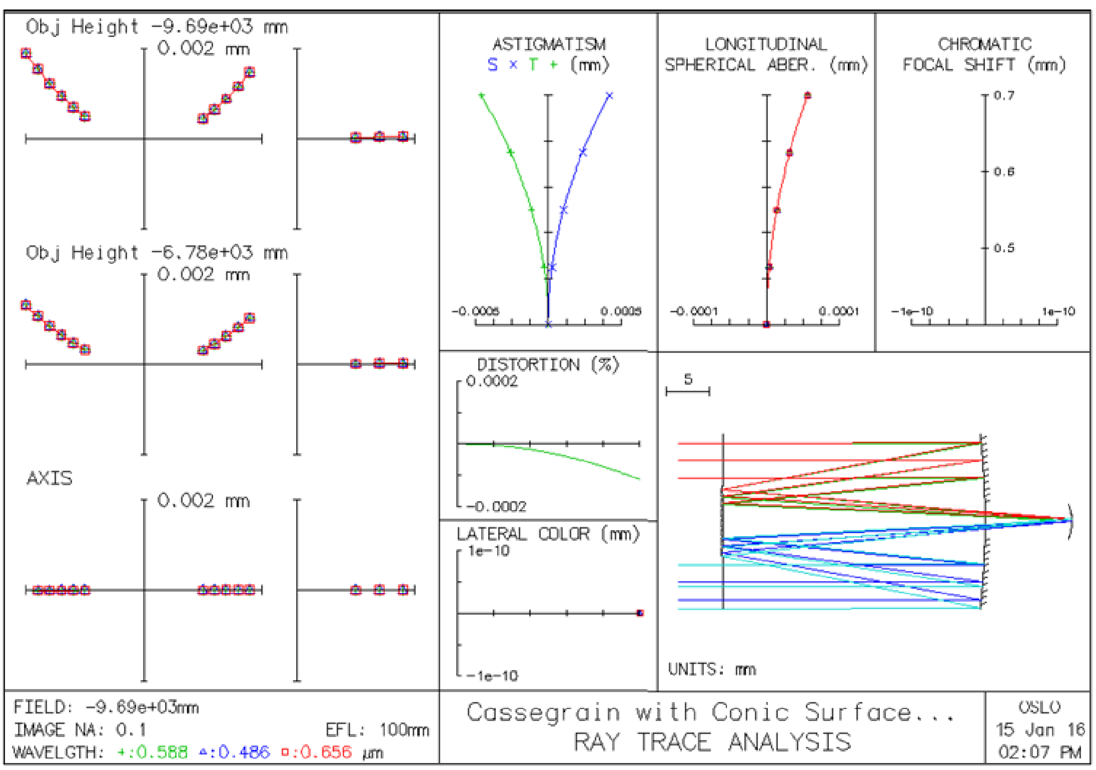


Figure 9: Ray trace analysis for a telescope with a curved focal plane array detector whose curvature is 400 mm.

Table 2 Aberrations as a function of focal plane array detector curvature for a telescope				
Curvature (mm)	Astigmatism (mm)	Coma (Distortion) %	Chromatic Aberration (x 10 mm)	Spherical Aberration (mm)
0	0.01	0.03	.012	0.2
300	0.008	0.001	0.003	0.005
350	0.003	0.0001	0.00006	0.006
400	0.007	0.00017	0	0.00005
500	0.001	0.006	0.006	0.004

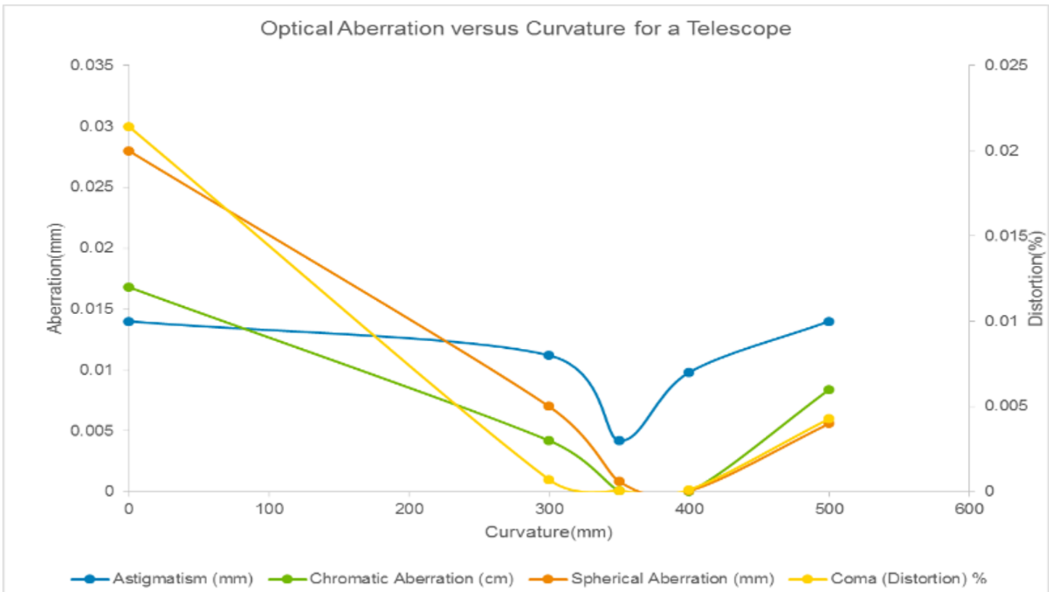
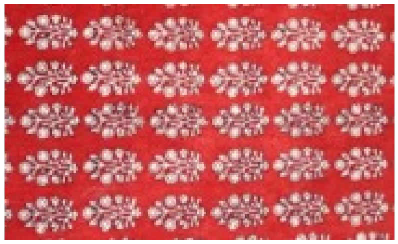


Figure 10: Variation of aberrations as a function of curvature of the focal plane array detector for a telescope.

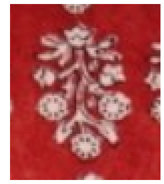
4.3 Optical Modeling Validity Tests Results

An image of a pattern on a fabric that was captured using a hand-held mobile phone camera that makes use of a flat focal plane array detector is shown in Figure 11a. Figure 11b shows the magnified view (6x) of the image from pixels around the center area and Figure 11c shows the magnified image (6x) from the edge pixels. Figure 12a shows the image of the same pattern, generated by the same mobile phone camera using the curved focal plane array detector technique described in Figure 4 above. Figure 12b shows the magnified view (6x) of the image from pixels around the center area and Figure 12c shows the magnified image (6x) from the edge pixels.



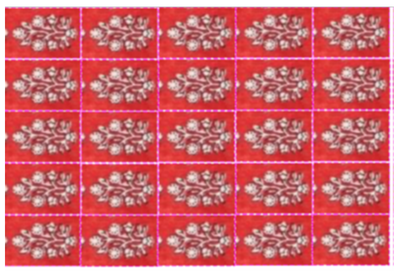
(a) Image captured with a mobile phone with a flat focal plane array detector.

(b) 6x magnification of center pixels of Fig. 11a.



(c) 6x magnification of edge pixels of Fig. 11a.

Figure 11: Mobile phone camera with flat focal plane array detector.



(a) Image captured with a mobile phone with a flat focal plane array detector using Petzval curvature simulation technique described in Fig. 4.

(b) 6x magnification of center pixels of Fig. 12a.

(c) 6x magnification of edge pixels of Fig. 12a.

Figure 12: Mobile phone camera with flat focal plane array detector using Petzval curvature simulation technique.

As shown in Figure 11a, the image of a pattern on a fabric taken by the camera with a flat focal plane array detector appears to have good quality throughout the frame at no magnification. As the image is magnified (6X), the quality of image is distorted somewhat and is not uniform anymore (see Figure 11b). The image quality around the center of the picture remained high at the 6x magnification level but decreased rapidly and becomes blurry away from the center of the image (compare Figure 11b to Figure 11c). On the other hand, Figure 12a, shows the reconstructed image as described above in Figure 4. As with the flat focal plane array detector image in Figure 11a, the image quality appears uniform throughout the scene at no magnification. However, at a 6X magnification, the image quality at the edge remains almost identical to that observed at the center. As the image is magnified further (greater than 6X), the image quality degrades more at the edge relative to the center. This experiment clearly indicates that if consumer hand-held cameras with curve focal plane array detectors can be designed and manufactured, they will produce quality images that are free from aberrations relative to those achieved using devices on today's market that make use of a flat focal plane array detector.

5. CONCLUSION

Currently, based on a survey of the literature in the field of optical focal planes, cameras with a curved focal plane array detector are extremely rare with the exception of research or commercial grade devices that are not at a reasonable price point for either small or large scale cameras and telescopes. This is primarily due to the fact that the fabrication of curved focal plane array detectors is extremely challenging in terms of manufacturing yields. Low manufacturing yields make optical curved focal plane array detector devices cost prohibitive for consumers. Various innovative fabrication techniques such as flexible silicon, semiconductor devices and membrane pressure systems[8] are currently being developed that will allow the production of low cost, high performance optical curved focal plane array detector systems to become a reality in the future. These next generation cameras and telescopes will have the advantage of a reduced number of optical elements that will result in much lighter and compact devices that will revolutionize the imaging field in the future, both here on Earth and above in space.

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REFERENCES

[1] Rim, S.-B., Catrysse, P. B., Dinyari, R., Huang, K., and Peumans, P., "The optical advantages of curved focal plane arrays," *Optics Express* **16**, 4965–4971 (Mar 2008).

[2] Shin, G., Jung, I., Malyarchuk, V., Song, J., Wang, S., Ko, H. C., Huang, Y., Ha, J. S., and Rogers, J. A., "Micromechanics and advanced designs for curved photodetector arrays in hemispherical electronic-eye cameras," *Small* **6**(7), 851–856 (2010).

[3] Iwert, O. and Delabre, B., "The challenge of highly curved monolithic imaging detectors," in [*High Energy, Optical, and Infrared Detectors for Astronomy IV*], Holland, A. D. and Dorn, D. A., eds., **7742**, 646 – 654, International Society for Optics and Photonics, SPIE (2010).

[4] Dilworth, D., [*Lens design: automatic and quasi-autonomous computational methods and techniques*], IOP Publishing (2018).

[5] Rosen, A. M., Denham, D. B., Fernandez, V., Borja, D., Ho, A., Manns, F., Parel, J.-M., and Augusteyn, R. C., "In vitro dimensions and curvatures of human lenses," *Vision Research* **46**(6), 1002 – 1009 (2006).

[6] Mark, D., "New optical modalities utilizing curved focal plane imaging detector devices and large arrays for terrestrial and spaceborne telescopes," in [*High Energy, Optical, and Infrared Detectors for Astronomy IV*], Holland, A. D. and Dorn, D. A., eds., **7742**, 707 – 714, International Society for Optics and Photonics, SPIE (2010).

[7] Shah, R., "Wide field-of-view curved focal plane array," *Tech Notes, Lincoln Laboratory Massachusetts Institute of Technology* (2012).

[8] Guenter, B., Joshi, N., Stoakley, R., Keefe, A., Geary, K., Freeman, R., Hundley, J., Patterson, P., Hammon, D., Herrera, G., and et al., "Highly curved image sensors: a practical approach for improved optical performance," *Optics Express* **25**, 13010–13023 (Jun 2017).